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A MODEL OF PHOTOCURRENT FLOW IN METAL-INSULATOR-SEMICONDUCTOR (MIS) STRUCTURE AT LOW ELECTRIC FIELDS IN THE INSULATOR

A model of photoelectric phenomena taking place in metal-insulator-semiconductor (MIS) structures, at low electric field in the insulator, has been recently developed and is shortly presented in this paper. Using this model, photoelectric characteristics of various MIS structures are calculated and are shown to agree well with the experimentally taken characteristics. Based on this model, new measurement methods have been worked out, of the physical parameters of MIS structures. One of such methods, the photoelectric measurement method of the φ_{MS} factor in MIS structures is presented in this paper and advantages of this method are discussed.

Key Words: MOS structures, photoelectric phenomena, contact potential

1. INTRODUCTION

The semiconductor industry worldwide, is roughly a 200 000 000 000 S a year business, in total sales value. Most of the products of this industry are built using the metal-insulator-semiconductor (MIS) structures as the basic building blocks. Hence, exact understanding of the physical properties of these structures (called also metal-oxide-semiconductor or MOS structures) is of paramount importance to the entire electronics industry. In many cases these physical properties can be most accurately determined using photoelectric methods. This however requires existence of models which explain relations between photoelectric characteristics of MIS structures and their basic physical parameters, such as e.g. the effective contact potential difference (φ_{MS}), which determines the threshold voltage (V_T) of MIS integrated circuits.

Such a model has been developed and is shortly presented in this paper. Based on this model, a measurement method has been worked out of the effective contact potential difference (φ_{MS}) in MIS structures. This method which will be also presented in this article, is the most accurate of the existing methods of this parameter determination.

2. NEED OF A MODEL

Photoelectric methods have been applied to determine some of the MIS structure physical properties since the early days of the semiconductor industry. Practically however, all of these methods were based on the physical model developed by Powell and Berglund (PB model) [1, 4, 5], which applies only when a relatively large electric field ($|E|>10^5$ V/cm) exists in the insulator. This means, that considering the photocurrent vs. gate voltage ($J=f(V_G)$) characteristics, the PB model applies outside of a certain box, shown schematically in Fig. 1, and until recently there was no model which would apply inside of this box, i.e. for low electric fields in the insulator.

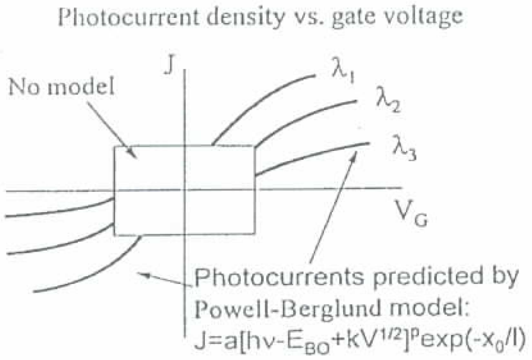

Fig. 1. Illustration of the region where the PB model applies

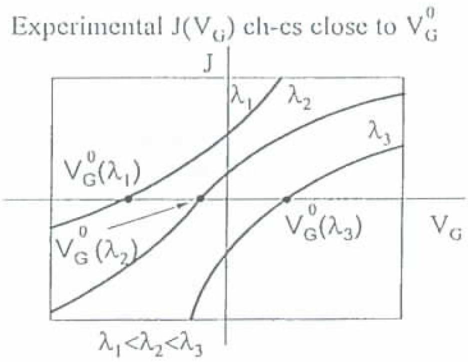

Fig. 2. Experimental photocurrent vs. gate voltage characteristics of a MIS structure, at low electric fields in the insulator

The general features of the experimental $J=f(V_G)$ characteristics, taken inside of the same box, are illustrated in Fig. 2. It should be noted, that the position of the zero-current point on the gate voltage axis, changes with the changing wavelength λ of the UV radiation illuminating the MIS structure. On the other hand, the gate voltage V_G^0 at which the photocurrent J is equal zero, can be measured very accurately (e.g. with the accuracy of $\pm$ 1 mV, or better) and this measurement can be easily automated. It was reasonable therefore, to expect that a model which correctly explains relations existing between V_G^0 values at various wavelengths λ and the basic physical parameters of the MIS structure, would allow accurate determination of these basic physical parameters. This was the primary motivation of our search for the model of photoelectric phenomena in MIS structures at low electric fields in the insulator.

3. DERIVATION OF THE MODEL

The object of our consideration is shown schematically in Fig. 3. An MIS structure with semitransparent gate is considered, which is uniformly illuminated by an UV illumination system. The wavelength λ of the UV radiation is variable over

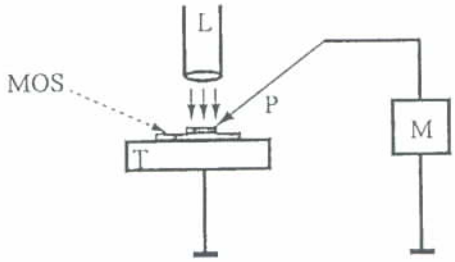

Fig. 3. Schematic illustration of the measurement setup used in this investigation. MIS: the MIS structure with semitransparent gate; *L*: UV illumination system; *P*: contact probe; *M*: voltage source and current measurement unit *T*; measurement stage

the range of values for which photoinjection of electrons from both the gate and the substrate takes place, into the conduction band of the dielectric. The gate bias V_G is variable over the range of values for which weak electric fields ($|E| < 10^5$ V/cm) exist in the insulator and the photocurrent is measured in the external circuit. In general, we would like to find out, what is the dependence of the photocurrent J on the gate bias V_G and on the wavelength λ.

Following assumptions are made in the derivation of the model:

- Only electrons are photoinjected into the conduction band of the insulator (photoinjection of holes is negligible).
- The current flowing across the dielectric is due both to drift and diffusion.
- There is a considerable space charge of density n, of electrons in the insulator. This space charge density consists of the density of free electrons n_C (which reside in the conduction band of the insulator) and of the density of trapped electrons n_T (which reside in traps of the insulator). It is also assumed that at any position in the insulator, a fixed fraction θ of the total electron density resides in the conduction band, while the remainder resides in traps.
- The problem may be considered as one dimensional.

With these assumptions, the problem is fully described by the following equations:

– The current flow equation.
– The Poisson equation.
– The $n_C = \theta n$ relation, resulting from the assumption given above.

Introducing dimensionless variables and combining these three equations, following third order differential equation is obtained [10]:

$$J = \frac{d^3\varphi}{dz^3} - \frac{d^2\varphi}{dz^2} \cdot \frac{d\varphi}{dz} \tag{1}$$

which should be solved, subject to the boundary conditions:

$$\frac{d^2\varphi}{dz^2}(z=0) = N(0); \quad \frac{d^2\varphi}{dz^2}(z=1) = N(1) \tag{2}$$

Here: J is dimensionless current, φ — dimensionless potential, z — dimensionless distance and $N(0)$, $N(1)$ dimensionless electron density, at $z=0$, $z=1$ respectively.

Equation (1) can be immediately integrated once and using the substitution:

$$\varphi=-2\ln y \tag{3}$$

following transitional equation is obtained:

$$\frac{d^2y}{dz^2}+\frac{1}{2}(Jz+C_1)y=0 \tag{4}$$

where C_1 is the first integration constant.

The transitional equation (4), can be solved both in case of $J=0$ and in case of $J\neq 0$. Here, only the solution for $J=0$ will be discussed.

Solution of eq. (4), for $J=0$, yields the following expression for the gate voltage V_G^O, for which the photocurrent J is equal zero [10]:

$$V_G^O=\frac{kT}{q}\left[\ln\frac{A(\lambda)}{T(\lambda)}+\ln\frac{(hv-E_{BG})^{p_G}}{(hv-E_{BS})^{p_S}}\right]+C \tag{5}$$

where kT/q is the diffusion potential, $A(\lambda)$, $T(\lambda)$ are fractions of UV radiation absorbed by the gate, substrate, hv is photon energy, E_{BG}, E_{BS} are barrier heights at gate-dielectric, substrate-dielectric interfaces, p_G, p_S are exponential factors used in the PB model [1, 4, 5] and C is a constant given by [10]:

$$C=\frac{kT}{q}\ln R+V_S^O+\varphi_{MS} \tag{6}$$

where R is a constant, V_S^O is semiconductor surface potential when $J=0$ and φ_{MS} is the effective contact potential difference between the gate and the substrate.

It should be noted that values of $A(\lambda)$ and $T(\lambda)$ in eq. (5) depend solely on the optical properties of the MIS structure and can be accurately calculated if the optical indexes of the involved layers (metal, insulator, semiconductor) are known (see e.g. [3]).

Hence, equation (5) allows calculation of the V_G^O vs. λ characteristic, for a given MIS structure, with the accuracy to the constant C. Moreover, it can be shown [10], that when electron densities at the gate-insulator interface (n_G) and at the semiconductor-insulator interface (n_S) become equal to each other, the $J=f(V_G)$ characteristic becomes symmetrical in relation to the $J=0$ point. In this case:

$$V_G^O=V_{GO} \tag{7}$$

where V_{GO} is the gate voltage at which the voltage drop in the insulator V_I is equal zero. This V_{GO} voltage, called zero dielectric voltage (ZDV) gate voltage is a useful quantity, which can be used to determine various parameters of MIS structures. (The band diagram of an MIS structure at ZDV gate voltage is shown in Fig. 6).

In Fig. 4 the V_G^O vs. λ characteristics, calculated using eq. (5), are shown for Al-SiO_2-Si structures with different thicknesses of the SiO_2 layer. As seen in Fig. 4, the $V_G^0(\lambda)$ curves significantly change their shapes with the changing thickness t_I of the SiO_2 layer. This property will be used in the next section to demonstrate agreement between the theory presented above and the experimental $V_G^0(\lambda)$ characteristics.

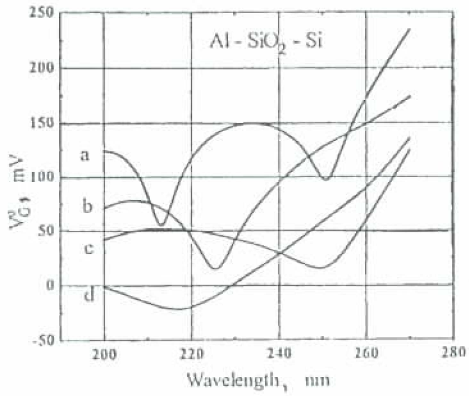

Fig. 4. The V_G^0 vs. λ curves calculated using eq. (5) for different thicknesses t_I of SiO_2 layer in a Al-SiO_2--Si structure. Values of the constant C have been arbitrarily chosen for each curve, so as to better show differences in shapes of the curves. a – t_I=400 nm, C=80 mV; b – t_I=280 nm, C=30 mV; c – t_I=150 nm, C=0; d – t_I=55 nm, C=0

4. EXPERIMENTAL VERIFICATION

A number of $V_G^0=f(\lambda)$ characteristics were taken for a series of Al-SiO_2-Si(N^+) and Al-SiO_2-Si(P^+) structures, to verify the model discussed above. The structures used for experimental verification differed only in the thickness (t_I) of the SiO_2 layer, which influences the shape of the $V_G^0(\lambda)$ curve, as shown in Fig. 4 and in the type (N^+ or P^+) of the silicon substrate, which influences the φ_{MS} value, thus influencing the value of the C-constant (see eq. (6)).

Examples of such experimental characteristics are shown in Fig. 5, in comparison with characteristics calculated using eq. (5). Values of V_{GO} are also marked on each of the characteristics shown in Fig. 5. The values of t_I and C used for calculation of the theoretical $V_G^0(\lambda)$ characteristics were chosen in such a way as to obtain the best fit between the theoretical curve and the experimental characteristic (t_I determines the shape of the theoretical curve and C determines the vertical shift of this characteristic).

Following statements can be made concerning the comparison of the $V_G^0=f(\lambda)$ curves calculated using eq. (5) with the experimentally taken $V_G^0(\lambda)$ characteristics:

- Very good agreement has been obtained between the shapes of the calculated and the experimental characteristics.
- Best fit SiO_2 layer thickness values (t_I) are (1.0÷4.5)% lower than the ellipsometrically measured t_I (ellips) values.

• Best fit C values correctly reflect differences in φ_{MS} values of the measured structures.

Thus, it can be concluded, that the model derived above correctly approximates the MIS structure behavior for the zero current ($J=0$), case.

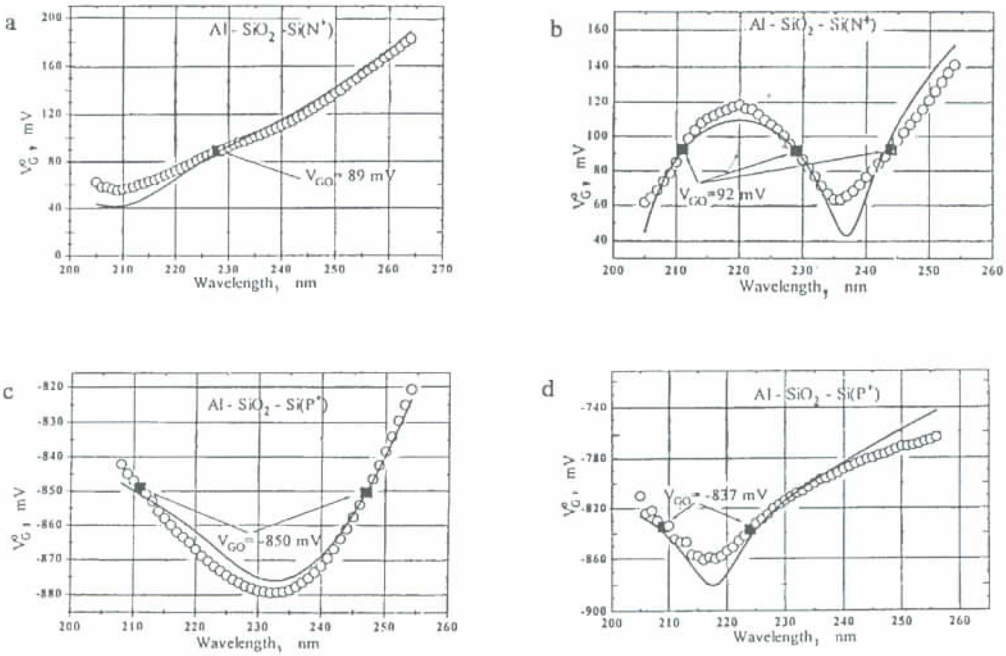

Fig. 5. Comparison of the $V_G^0 = f(\lambda)$ curves calculated using eq. (5) (solid lines), with the experimentally taken $V_G^0(\lambda)$ characteristics (circles), for Al-SiO_2-Si(N^+) and Al-SiO_2-Si(P^+) structures, with different thicknesses t_I of the SiO_2 layer. Best fit t_I and C values are given below as well as the values of the ellipsometrically measured thickness t_I (ellips) of the SiO_2 layer. a – $t_I=51.5$ nm, $C=74$ mV, t_I (ellips.)=52 nm; b – $t_I=375$ nm, $C=50$ mV, t_I (ellips.)=385.9 nm; c – $t_I=62$ nm, $C=-872$ mV, t_I (ellips.)=63.5 nm; d – $t_I=196$ nm, $C=-855$ mV, t_I (ellips.)=204.2 nm

5. APPLICATION OF THE MODEL

The model discussed above has found applications in measurement methods of the basic physical parameters of MIS structures. Following is the description of one of such methods – the photoelectric method of determination of the effective contact potential difference (ECPD) between the gate and the substrate of MIS structures. The principles of this method were proposed already in the early eighties [2, 6, 7]. However, the firm theoretical background of the method has been established, as well as its high precision has been made available after the model discussed above had been developed [10].

The threshold voltage V_T of MOS transistors is the single most important parameter of MOS integrated circuits (MOS IC_S. In modern ultra large scale of integration (ULSI) IC_S, it is the ECPD – called also the φ_{MS} factor – which significantly influences the V_T value. Hence, it is important to know what precisely the value of φ_{MS} is, in a given MOS structure.

The photoelectric method of φ_{MS} determination is based on following considerations. It is well known from the theory of MIS structures, that in general, the gate voltage V_G is given by the sum:

$$V_G = V_I + V_S + \varphi_{MS} \tag{8}$$

where V_I is the voltage drop in the insulator and V_S is the semiconductor surface potential. When the voltage drop in the insulator is equal zero ($V_I=0$), the band diagram of the MIS structure looks as shown in Fig. 6 and from eq. (8), we have:

$$V_{GO} = V_{SO} + \varphi_{MS} \tag{9}$$

where V_{GO} is the ZDV gate voltage and V_{SO} is the semiconductor surface potential for $V_G = V_{GO}$.

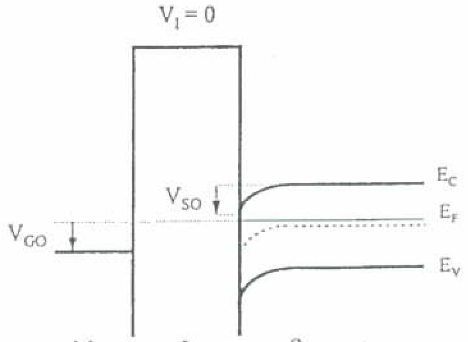

Fig. 6. The energy band diagram of an MIS structure biased with V_{GO} gate voltage at which $V_I=0$

The value of V_{GO} can be measured with high accuracy, as discussed in section 3 and illustrated in section 4. Hence, to accurately determine φ_{MS}, the value of V_{SO} has to be known.

There are two principal ways of dealing with the V_{SO} value. Either we can determine V_{SO} with a separate measurement, or we can make it negligible in comparison with φ_{MS}.

The value of V_{SO} can be determined by taking the C (V_G) characteristic of the MIS structure under consideration and determining the capacitance value C (V_{GO}), which corresponds to the V_{GO} gate bias. From the C (V_{GO}) value, V_{SO} can be calculated by standard methods and φ_{MS} can be determined using eq. (9).

The value of V_{SO} can be made negligible in comparison with φ_{MS} in several ways, but the simplest way to achieve this goal is to use MIS structures with heavily doped substrates. This way, V_{SO} can easily be made as small as $V_{SO} < 5$ mV and from eq. (9), $\varphi_{MS} \cong V_{GO}$ in this case.

The photoelectric φ_{MS} measurement method described above has been shown to be an order of magnitude more accurate than the classical method used previously [8]. At present, the accuracy of this method is estimated to be, in general, better than ± 20 mV, while in the case of optimized samples it is better than ± 5 mV.

This method has been successfully applied in several investigations aimed at determining the influence of various factors on the ECPD in MIS structures. A more detailed discussion of this problem, as well as the bibliography of these investigations can be found in [9].

6. CONCLUSIONS

A model has been developed for the photocurrent flow in metal-insulator--semiconductor structures at low electric fields in the insulator. It has been shown that photoelectric characteristics, calculated using this model for various MIS structures, agree well with the experimental characteristics.

This model has found application in developing new measurement methods of the important physical parameters of MIS structures. In particular, the photoelectric method of the φ_{MS} factor determination, described in this paper, has been proved to be easier in application and much more accurate than the classical method used previously.

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MODEL PRZEPŁYWU FOTOPRĄDU W STRUKTURZE MIS PRZY MAŁYCH NATĘŻENIACH POLA ELEKTRYCZNEGO W DIELEKTRYKU

Streszczenie

Współczesna mikroelektronika wymaga wielkiej dokładności określania parametrów układów scalonych oraz utrzymania wartości tych parametrów w bardzo wąskich przedziałach tolerancji. Jednocześnie, właściwości fizyczne struktur, które określają wartości tych parametrów, często nie mogą być zmierzone z porównywalną dokładnością. Stąd np. często konieczne jest eksperymentalne określanie warunków produkcji układów scalonych, kosztowną metodą prób i błędów.

Coraz ważniejsze staje się więc opracowywanie dokładnych metod pomiaru podstawowych właściwości fizycznych struktur metal-dielektryk-półprzewodnik (ang. MIS – metal-insulator-semiconductor). Opracowanie takich metod wymaga niekiedy nowych modeli fizycznych rozważanych zjawisk i struktur. Taki właśnie przypadek zaistniał w opisanych tu badaniach.

Fotoelektryczne metody pomiarowe znalazły szerokie zastosowanie w określaniu właściwości fizycznych struktur MIS. Jednak stosowane dotychczas metody, opierały się na modelu fizycznym, który słuszny jest tylko wtedy, gdy w dielektryku struktury istnieje względnie silne pole elektryczne ($|E| > 10^5$ V/cm). Nasze badania wykazały natomiast, że niektóre parametry fizyczne struktur MIS, takie jak np. efektywna kontaktowa różnica potencjałów (EKRP) pomiędzy bramką a podłożem mogą być najdokładniej zmierzone w warunkach bardzo słabych pól elektrycznych w dielektryku. To właśnie stało się powodem opracowania opisanego tu modelu. Wykorzystując równanie ciągłości, równanie Poissona związek pomiędzy koncentracjami elektronów przewodnictwa i elektronów spułapkowanych w dielektryku oraz biorąc pod uwagę właściwości optyczne struktur MIS, opracowano model pozwalający określać wartości fotoprądów w tej strukturze, w funkcji potencjału bramki i w funkcji długości fali promieniowania padającego na strukturę. Porównanie obliczonych na podstawie tego modelu charakterystyk, z charakterystykami eksperymentalnymi potwierdza słuszność modelu.

Opracowana przez nas metoda pomiaru EKRP w strukturach MIS, która wykorzystuje ten model, jest najdokładniejszą ze znanych metod pomiaru tego parametru.